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REVIEW

Marine birds and plastic debris in Canada: a national synthesis and a way forward

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Abstract: Marine plastic ingestion by seabirds was first documented in the 1960s, but over 50 years later our understanding about the prevalence, intensity, and subsequent effect of plastic pollution in the oceans is still developing. In Canada, systematic assessments using recognized standard protocols began only in the mid-2000s. With marine plastic pollution identified by the United Nations Environmental Program (UNEP) as one of the most critical challenges for the environment, a greater understanding of how plastics affect marine birds in Canada, along with a national strategy, is timely and necessary. To better understand which and how many marine birds are affected by marine debris, we reviewed reports of plastic ingestion and nest incorporation in Canada. Of the 91 marine bird species found in Canadian waters, detailed plastic ingestion data from multiple years and locations are available for only six species. Another 33 species have incidental reports, and we lack any data on dozens more. Future efforts should focus on characterizing the risk of plastic ingestion among understudied species and on continued monitoring of species that are known indicators of plastic pollution internationally and found in multiple regions of Canada to facilitate comparisons at the national and international levels.

Key words: plastic, seabirds, marine birds, Canada, debris.

Résumé : Déjà dans les années 1960, sont parus des documents faisant état de l'ingestion de plastique par les oiseaux marins, mais 50 ans plus tard notre compréhension sur la prévalence, l'intensité et les effets subséquents de la pollution par le plastique dans les océans est toujours en développement. Au Canada, des évaluations systématiques basées sur des protocoles standard reconnus ont débuté seulement au milieu des années 2000. La pollution marine par le plastique ayant été reconnue par le Programme des Nations Unies pour l'environnement (PNUE) comme un des défis les plus critiques pour l'environnement, il est nécessaire d'avoir une meilleure compréhension de la façon avec laquelle les plastiques affectent les oiseaux marins au Canada; le temps est venu de développer une stratégie nationale qui s'impose. Afin de mieux comprendre quels sont les espèces et les nombres d'oiseaux de mer affectés par les débris marins, les auteurs ont revu les rapports sur l'ingestion de plastique et son incorporation dans les nids au Canada. Sur les 91 espèces d'oiseaux marins répertoriés dans les eaux canadiennes, on ne retrouve des données détaillées provenant de nombreuses années et locations que pour six espèces. On retrouve des rapports occasionnels pour 33 espèces et il n'existe aucune donnée pour d'autres douzaines d'espèces. Les futurs efforts de suivi devraient se concentrer sur la caractérisation du risque de l'ingestion de plastique chez les espèces sous étudiées et sur le suivi continu des espèces réputées indicatrices de la pollution partout au monde, présentes dans plusieurs régions du Canada, afin de faciliter les comparaisons aux échelles nationale et internationale. [Traduit par la Redaction]

Mots-clés : plastique, oiseaux marins, oiseaux de mer, Canada, débris.

Introduction

Background

Plastic debris in the marine environment has been identified by the United Nations Environment Programme (UNEP) as a critical emerging global environmental issue (UNEP 2011, 2014). Plastic pollution is increasing, especially in the oceans, and one of the fundamental challenges identified by the UNEP is how to best assess and monitor plastic pollution in the marine environment (Thompson et al. 2004; Moore 2008; Ryan et al. 2009; UNEP 2011; Depledge et al. 2013). Only one region, the North Sea, has regular, coordinated monitoring of marine plastic debris that is supported by policy and a network of researchers (UNEP 2011; van Franeker et al. 2011). To date, most efforts to monitor and track plastic pollution in the marine environment have been ad hoc, opportunistic, and largely uncoordinated among jurisdictions.

Marine pollution is problematic for a variety reasons. From an economic perspective, marine litter can interfere with subsistence fishing practices causing changes in practices and potential income (Nash 1992). Additionally, plastic pollution can negatively affect ecotourism by creating unappealing coastal land and seascapes (Gregory 1999; Jang et al. 2014). It can also impede conservation efforts, and interfere with larger policy objectives (Mouat et al. 2010; Hastings and Potts 2013; Vegter et al. 2014). Clean-up of marine pollution is extremely costly, reaching millions of dollars a year, making plastic pollution a major cost for local and regional governments (Mouat et al. 2010; UNEP 2014; Vegter et al. 2014).

There are two types of plastics in the ocean: industrial and user plastics. All plastics are manufactured from oil, and during the refinement process hydrocarbons are formed into industrial pellets, or nurdles, for shipping purposes. These pellets are the

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primary source for the plastics industry, and they are shipped worldwide in large containers on sea-going shipping vessels. Plastic pellets are accidentally released into the marine environment regularly, where they are persistent and disperse widely (Gregory and Ryan 1997). Once pellets reach plastic production factories, they are melted down and formed into specific shapes that go on to become toys, kitchen gadgets, computers, furniture, food packages, drink containers, and many other consumer or user products.

Although marine organisms encounter and ingest wood and other natural debris regularly (e.g., Couch 1838; Hindwood 1946), since World War II plastics have also littered marine waters (Thompson et al. 2004; Moore 2008), and they are reported more frequently as a problem for wildlife (Laist 1997). Many groups of animals interact with plastic pollution, including marine mammals, fish, sea turtles, sea snakes, and seabirds (Laist 1997; Boerger et al. 2010, Bravo Rebolledo et al. 2013; Udyawer et al. 2013; Baulch and Perry 2014). Even invertebrates such as copepods, polychaetes, mussels, and squid may ingest small fragments of plastics (Day 1988; Browne et al. 2008; Moore 2008; Goldstein and Goodwin 2013). Because marine plastics can be positively buoyant, these marine predators are susceptible to encountering such plastic pollution while feeding in surface waters (Baulch and Perry 2014). Such interactions with marine pollution can negatively affect wildlife, both directly and indirectly, and may have ecological implications.

One reason why plastics were popularized is their durability. Plastics do not break down into component chemicals without extraordinary heat, but they rather just become smaller in size over time in the environment. Plastic items such as bottles and buoys can be initially released into the environment as whole items, but as they are exposed to weathering by wind, waves, and ultraviolet light the plastics are broken down in to smaller and smaller pieces. Over time, large plastic products can lead to microplastics, pieces of plastics smaller than 5 mm in diameter, and as small as 0.004 μm (UNEP 2014). Microplastics are also used in some commercial products such as beauty scrubbers and exfoliates, thus entering oceans from both a primary source of products and as a secondary product of larger plastic breakdown in the environment (Eriksen et al. 2013). Wildlife have been documented to have interactions with both macro- and microplastics (Provencher et al. 2009; Boerger et al. 2010; van Franeker et al. 2011).

Direct interactions between wildlife and plastics include wildlife entanglement in debris, either at the surface of the water or in subtidal habitat (Carretta et al. 2013; Waluda and Staniland 2013). Entanglement can cause distress in animals (Raum-Suryan et al. 2009) and, in some cases, cause fatalities of hundreds of individuals (Good et al. 2010). Seabirds also directly interact with plastics through collecting floating plastic debris and using it to construct their nests. Nest incorporation of plastics is a relatively easy and noninvasive technique to assess composition of plastics encountered by seabirds, as well as document trends over time (Votier et al. 2011; Bond et al. 2012; Lavers et al. 2013).

Additionally, one of the largest concerns with marine plastic pollution is the effect that ingested pollution has on wildlife (Ryan et al. 2009). It is thought that birds, and most likely all marine predators, mistake plastics floating in the marine environment for prey species (Cadée 2002). Ingested plastics can have a variety of negative effects on seabirds, including reduced appetite, growth, and dietary efficiency (van Franeker 1985; Dickerman and Goelet 1987; Ryan 1988). Although the specific effects of plastics on many species is unknown, for seabirds already stressed by altered food webs, increasing environmental contamination, and emerging diseases (Kitaysky and Golubova 2000; Mavor et al. 2008), ingested plastics is an additional stressor that may have synergistic, deleterious effects.

Recent work has also shown that ingestion of plastics can also lead to indirect effects, such as increased exposure to contaminants (Teuten et al. 2009; Rochman et al. 2013). In addition to containing chemicals used in plastic production, studies of beached plastic pollution have shown that plastic debris absorb chemicals from the surrounding water (Endo et al. 2005), including DDT, polychlorinated biphenyls (PCBs), and toxic trace elements (Endo et al. 2005; Teuten et al. 2009). Some plastics recovered from the marine environment have levels of contaminants in excess of the surrounding sediments (Holmes et al. 2012).

Once ingested by wildlife, these chemically loaded plastics enter the digestive tract of the bird (Teuten et al. 2009). The plastics themselves may contain chemicals that may be released in the digestive tract as plastic pieces are broken down (Tanaka et al. 2013; Bakir et al. 2014). Plastic pieces can also contain hydrophobic compounds absorbed during their time in the marine environment that can desorb in the oily digestive system of fish- and plankton-eating marine birds and mammals, exposing wildlife to a range of contaminants (Teuten et al. 2009; Colabuono et al. 2010; Lavers et al. 2014). Importantly, plastic and contaminant type may influence the desorption rates of chemicals on and in plastics within the gut (Bakir et al. 2014), suggesting that wildlife may be more exposed to some contaminants than others through ingested plastics.

Although plastic entanglement and ingestion in marine animals has been reported for hundreds of species (Laist 1997), seabirds have been identified both within the scientific literature and through existing policy as useful indicator, or sentinel species, for marine pollution (OSPAR 2008; van Franeker et al. 2011). Seabirds are particularly good indicator species for marine plastics because they can forage over large areas, essentially sampling over their entire range for plastics. Additionally, many seabirds breed in colonies that are relatively easy to access for study purposes (Piatt et al. 2007). Consequently, sufficient samples can be gathered from working at a single location where the birds are sampling across a large marine habitat, which is much more efficient than researchers trying to sample at sea. Seabirds are also found as beached birds in many regions, providing samples that are easily obtained with little collection effort. For these reasons, when discussing marine plastic pollution monitoring and research, seabirds lend themselves as particularly useful study species (van Franeker et al. 2011).

In Canada, ingested marine plastic pollution has been reported on all three coastlines in seabirds (e.g.,Threlfall 1968; Blight and Burger 1997; Mallory et al. 2006). With a growing number of records for ingested plastics available for species in Canada, seabirds are among the most studied group for plastic interactions. The first records of plastic ingestion by Canadian seabirds are from the early 1960s (Threlfall 1968; Rothstein 1973). Since this time, ingested plastics have often been reported as a part of dietary studies (Braune and Gaskin 1982; Gilliland et al. 2004). With an increasing awareness of the impacts marine plastic debris have on seabirds, there has been a marked increase in reports of plastic ingestion both globally (Ryan et al. 2009) and across Canada (Mallory et al. 2006; Avery-Gomm et al. 2013; Bond and Lavers 2013).

Almost 50 years after the first reported plastic ingestion by a seabird in Canada, there is no existing strategy to assess the prevalence, intensity, and changes in plastic pollution in the Canadian environment. Our goals here were to review the current state of knowledge of direct interactions between plastics and marine birds in Canada, to identify knowledge gaps within this research area, and recommend ways to improve our understanding of ingested plastic debris through future research efforts.

In this review, we addressed only ingestion and nest incorporation of plastics, and we have left seabird entanglement in plastics for separate consideration. The rationale behind this division was that although entanglement may be a hazard to seabirds (e.g., Good et al. 2010), bird entanglement is a habitat obstacle, while nest incorporation and ingestion (studied through necropsy, forced regurgitation, or recovered regurgitations (or boluses)) represent active interaction with plastics and indicate plastic interactions on a larger scale, and over a time period beyond a single event. As we were interested in the long-term patterns, trends, and effects between seabirds and plastics, we focused on the active interaction between plastics and seabirds, rather than the passive encounter phenomenon of entanglements.

Approach

We limited our discussion to seabirds as categorized by Gaston (2004), which includes tubenoses (Procellariiformes), cormorants and gannets (Pelecaniformes), and selected phalaropes, gulls, terns, skuas, and auks (Charadriiformes). Loons (Gaviiformes) were also included here as most species spend large portions, if not their entire year, at sea (Gaston 2004). Additionally, we also included marine sea ducks and mergansers (Anseriformes; Merginae only) in our discussions. We did not consider some birds that are marine associated, such as kingfishers (Alcadinidae) or grebes (Podicepedidae); although some individuals may be mostly marine (e.g., coastal kingfishers), or parts of their annual cycle may be spent in the marine environment (e.g., grebes), as a group these birds are not likely to reflect conditions in the marine environment.

We limited our review to Canadian waters. Only birds collected from colonies, beaches, or waters within the Canadian Exclusive Economic Zone (EEZ) were included. Although there are regions in Canada where regional assessments may be more indicative of local trends (e.g., the Salish Sea, which includes waters from both Canada and the USA), for the purpose of identifying data assets and gaps we limited the discussion to birds found within Canada. Species known to breed in Canada were included as well as migrants that are regularly found in Canadian waters (Brown et al. 1975; Kenyon et al. 2009; Gjerdrum et al. 2012). Although we recognized that other species may be found in Canadian waters, we felt that rarities did not add substantially to the discussion regarding plastic pollution monitoring and research within our specified geographic region.

Of seabirds that are regularly found in Canadian waters there are two groups: breeders (those that breed on Canadian shores) and migrants (species that regularly use Canadian waters in the nonbreeding season and are, therefore, often found as by-catch and beached birds in Canada). Both groups can add to our knowledge of plastic ingestion in marine birds, specifically when assessing geographic spread of plastic pollution, an identified priority question (Depledge et al. 2013). We generated a list of seabird species found in Canadian waters and took their breeding or migrant status from Kenyon et al. (2009) and Brown et al. (1975), which covers all three of Canada's coastlines.

We reviewed the available literature for plastics ingestion and nest incorporation for seabirds found in Canada. Much of the data were published, but older records, prior to 2006, exist within more general reports rather than publications focused solely on plastic ingestion. Reported ingested plastics are presented as prevalence of plastics following van Franeker and Meijboom (2002), the number of birds within a sample to contain at least one piece of plastic, and consider only anthropogenic debris (i.e., excluding rocks, pumice, wood, etc.). We also use the mean mass of plastics within a sample of seabirds, which includes plastics found within the digestive tracts, including individuals that contained no plastics (van Franeker and Meijboom 2002).

Plastic ingestion in seabirds includes both macroplastics (plastics greater than 5 mm) and microplastics (less than 5 mm; UNEP 2014). Although average size of ingested/regurgitated plastic items is sometimes reported, seabird ingestion reports often do not differentiate between macroplastics and microplastics. Thus, we present ingested plastics as a single unit for purpose of this report, which includes both microplastics and macroplastics. Plastic incorporation in nests is indicative of larger pieces of plastics that have been picked up by birds during nest construction and would include only macroplastics.

We also used existing published data sets of prevalence to conduct a power analysis to assess the sample size needed to detect change in plastic ingestion over time following van Franeker and Meijboom (2002). We estimated the sample size required to detect changes from 5% to 100% (in 5% increments) in the frequency of plastic ingestion in thick-billed murres (*Uria lomvia*), common murres (*Uria aalge*), and northern fulmars (*Fulmarus glacialis*), and changes in the frequency of nest incorporation in northern gannets (*Morus bassanus;* see below for the rationale for including these species). We used the equation

$$n = 2 \times \left\{ \frac{[z_{\alpha/2} - z_{\pi}] \times \frac{\mathrm{CV}}{100} \times \mu_{\mathrm{I}}}{\mu_{\mathrm{I}} - 100} \right\}^2$$

where n is the sample size required, z is the t value, α is the Type I error (false positive) rate, π is the Type II error (false negative) rate, μ_{I} is the difference to detect (where $\mu_{\mathrm{I}} = 105$ indicates a 5% difference, 110 is a 10% difference, etc.), and CV is the coefficient of variation (mean ± SD) in the time series (van Zutphen et al. 1998). We set $\alpha = 0.05$ and $\pi = 0.90$, meaning that $z_{\alpha/2} - z_{\pi} = 3.242$ (van Franeker and Meijboom 2002). This calculation allowed us to estimate how many samples are required on an annual basis to construct a reliable data set (van Franeker and Meijboom 2002).

The current state of knowledge

Of the 91 seabird species that commonly occur in Canada's waters at least one individual from 39 species (43%) has been examined for ingested plastics or plastic incorporation into nests (Table 1; Fig. 1). Although this is an encouraging number, when we examined the details of the reports to date, we found that 24 of the 39 species were only single reports of plastic interactions, often with small sample sizes. This leaves only 15 species (17%) where reports for plastic interactions exist for more than one location and (or) time period. In fact, only six species (7%) have been sampled repeatedly in multiple regions and in multiple years. Of the above species examined for plastic, 37 species have been examined for plastic ingestion through either necropsy or regurgitates of some kind (Fig. 2), while nest incorporation of plastic has been studied in three species (Table 2).

For which species can we accurately examine frequency of ingestion or nest incorporation?

van Franeker and Meijboom (2002) found that in the Dutch Sea a sample size of 40 birds was needed to assess changes in ingested debris rates over time using necropsies. Only three species in Canada currently meet or exceed this sample size in one year and in a single region: northern fulmars, thick-billed murres, and common eiders (*Somateria mollissima*). van Franeker and Meijboom (2002) also showed that smaller sample sizes tend to result in greater variability. Although small samples can give us information on rarely-found species, analysis of small samples for trends is likely to result in estimates that sharply differ from regional population means, possibly producing spurious results.

To get a better understanding of the sample sizes needed in Canada, a power analysis was conducted using existing data from plastic ingestion in thick-billed murres, common murres, and northern fulmars. The power analysis suggested that varying, but relatively similar order of magnitude, numbers are needed in Canadian waters to detect changes in plastic pollution (Fig. 3). Results differed by region because of the differences in the prevalence of ingestion or incorporation among regions, and by the level of detectable change desired (Fig. 3). For Newfoundland thick-billed and common murres, based on current occurrence levels, 205 and 2060 birds would be needed each year to

Table 1. Species categorized by the type of ingested plastics data that is available in Canadian waters.

Species with recently ingested plastic, data reported from multiple locations and years (See Table 3)	Species with ingested plastic, data reported from multiple locations or years	Species with single reports of ingested plastic	Species currently with no reports of ingested plastic
Northern fulmar (*Fulmarus glacialis*)	Great shearwater (*Puffinus gravis*)*	Red-throated loon (*Gavia stellata*)	Yellow-billed loon (*Gavia adamsii*)
Leach's storm-petrel (*Oceanodroma leucorhoa*)	King eider (*Somateria spectabilis*)	Pacific loon (*Gavia pacifica*)	Laysan albatross (*Phoebastria immutabilis*)*,†
Sooty shearwater (*Puffinus griseus*)*	Common eider (*Somateria molissima*)	Common loon (*Gavia immer*)	Short-tailed albatross (*Phoebastria albatrus*)*
Northern gannet (*Morus bassanus*)	Surf scoter (*Melanitta perspicillata*)	Black-footed albatross (*Diomedea nigripes*)*,†	Mottled petrel (*Pterodroma inexpectata*)*
Common murre (*Uria aalge*)	Ivory gull (*Pagophila eburnea*)	Cory's shearwater (*Calonectris diomedea*)*,†	Murphy's petrel (*Pterodroma ultima*)*
Thick-billed murre (*Uria lomvia*)	Arctic tern (*Sterna paradisaea*)	Fork-tailed storm-petrel (*Oceanodroma furcata*)	Buller's shearwater (*Puffinus bulleri*)*
	Atlantic puffin (*Fractercula arctica*)	Stejneger's petrel (*Pterodroma Iongirostris*)*	Pink-footed shearwater (*Puffinus creatopus*)*
	Razorbill (*Alca torda*)	Double-crested cormorant (*Phalacrocorax auritu*)	Flesh-footed shearwater (*Puffinus carneipes*)*,†
	Rhinocerous auklet (*Cerorhinca monocerata*)	Harlequin duck (*Histrionicus histrionicus*)	Short-tailed shearwater (*Puffinus tenuirostris*)*
		Long-tailed duck (*Clangula hyemalis*)	Manx shearwater (*Puffinus puffinus*)
		Bonaparte's gull (*Chroicocephalua philadelphia*)	Audubon's shearwater (*Puffinus lherminieri*)*
		Glaucous-winged gull (*Larus glaucescens*)	Wilson's storm-petrel (*Oceanites oceanicus*)
		Great black-backed gull (*Laurs marinus*)	Great cormorant (*Phalacrocorax carbo*)
		Herring gull (*Larus smithsonianus*)	Pelagic cormorant (*Phalacrocorax pelagicus*)
		Common tern (*Sterna hirundo*)	Brandt's cormorant (*Phalacrocorax urile*)*
		Black-legged kittiwake (*Rissa tridactyla*)	Black scoter (*Melanitta americana*)
		Pigeon Guillemot (*Cepphus columba*)	White-winged scoter (*Melanitta deglandi*)
		Marbled murrelet (*Brachyramphus marmoratus*)	Barrow's goldeneye (*Bucephala islandica*)
		Xantu's murrelet (*Synthliboramphus hypoleucus*)*	Common goldeneye (*Bucephala clangula*)
		Ancient murrelet (*Synthliboramphus antiquus*)	Bufflehead (*Bucephala albeola*)
		Cassin's auklet (*Ptychoramphus aleuticus*)	Red-breasted merganser (*Mergus serrator*)
		Horned puffin (*Fratercula corniculata*)	Common merganser (*Mergus merganser*)
		Tufted puffin (*Fratercula cirrhata*)	Red phalarope (*Phalaropus fulicarius*)
		Dovekie (*Alle alle*)	Red-necked phalarope (*Phalaropus lobatus*)
			Parakeet auklet (*Aethia psittacula*)*,†
			Great skua (*Stercorarius skua*)*
			South polar skua (*Stercorarius maccormicki*)*
			Pomarine jaegar (*Stercorarius pomarinus*)
			Parasitic jaegar (*Stercorarius parasiticus*)
			Long-tailed jaegar (*Stercorarius longicaudus*)
			Heerman's gull (*Larus heermani*)
			Franklin's gull (*Leucophaeus pipixcan*)
			Laughing gull (*Larus atricilla*)
			Black headed gull (*Larus ridibundus*)
			Little gull (*Larus minutus*)
			Ross's gull (*Rhodostethis rosea*)
			Ringed-bill gull (*Larus delawarensis*)
			Mew gull (*Larus canus*)
			Common gull (*Larus canus canus*)*
			California gull (*Larus californicus*)
			Glaucous gull (*Larus hyperboreus*)
			Iceland gull (*Larus glaucoides glaucoides*)
			Kumlien's gull (*Larus glaucoides kumlieni*)
			Thayer's gull (*Larus thayeri*)
			Western gull (*Larus occidentalis*)*
			Lesser black-backed gull (*Larus fuscus*)
			Sabine's gull (*Xema sabini*)
			Caspian tern (*Sterna caspia*)
			Roseate tern (*Sterna dougalii*)
			Forster's tern (*Sterna forsteri*)
			Black tern (*Chlidonias niger*)
			Black guillemot (*Ceppheus grylle*)

*Indicates migrant species.
†Indicates species occurring in low numbers in Canadian waters and where plastic ingestion is studied elsewhere.

Fig. 1. Common seabird species in Canada. (A) Leach's storm-petrel (photo courtesy of Donald Pirie-Hay), (B) herring gulls, (C) thick-billed murre, (D) common murre, (E) northern gannet, (F) double-crested cormorant colony (photo courtesy of Craig Hebert), and (G) northern fulmars.

detect a 10% detectable change in plastic ingestion occurrence (Figs. 3A and 3B). Samples sizes for both murre species are well below this level in most sampling years. To detect a difference in ingestion occurrence in common murres at the 25% detectable change, 42 thick-billed and 106 common murres would be needed annually (Fig. 3). For thick-billed murres sample sizes often reach 42, suggesting that we do have the power to assess a 25% detectable change, whereas common murre sample sizes on average rarely exceeds a few dozen birds, indicating that we currently do not have the power to detect even a 25% change (Table 2).

For northern fulmars in the Canadian Arctic, the power analysis revealed that approximately 648 fulmars are needed annually to yield accurate results and detect changes up to 10% (Table 2; Fig. 3C). Current sample sizes for Arctic Canada are not this high, but they are adequate to detect a 25% change (Table 3). Samples sizes to have the power to detect a 25% detectable change (n = 134) is not available from the Arctic region to date. For northern fulmars sampled at Sable Island, on the Atlantic coast, only 61 birds per year are needed for a 10% detectable change, and only 13 birds are needed for a 25% detectable change in plastic ingestion occurrence due to the higher levels of plastic ingestion (Table 2; Fig. 3D). With sample sizes on Sable Island often exceeding 13 birds, we are able to accurately detect trends and levels within this species at this site at the 25% detectable change level (Table 3).

We also carried out a power analysis to estimate needed sample sizes to detect differences in plastic incorporation in northern gannet nests. At Funk Island, 629 nests per year need to be analyzed annually to detect a 10% change, whereas only 140 nests per year need to be assessed at the Cape Saint Mary's northern gannet colony (Figs. 3E and 3F). As past sampling at both of these colonies is well above these suggested values (Bond et al. 2012), it suggests that annual sampling efforts at this magnitude would allow for reliable determination of plastic incorporation in nests.

What species are ingesting plastics at a high incidence?

Eight species had a prevalence of ingested plastics that exceeded 50% (Table 2). Several species are reported to have very high levels of ingested plastics (e.g., 100% in black-footed albatross (*Phoebastria nigripes*), 100% in Stejneger's petrel (*Pterodroma longirostris*)), but sample sizes were very low (e.g., n = 3 for black-footed albatross and n = 1 for Stejneger's petrel; Blight and Burger 1997). Although in total eight species exhibited ≥50% prevalence of plastic ingestion in birds sampled, only three species had sample sizes >40. As a result, the only species that we can confidently say have a high prevalence of ingested plastics in Canada, with data that likely reflect a regional mean, are northern fulmars (Pacific and Atlantic, but not the Arctic), sooty shearwaters (*Puffinus griseus*; in the Atlantic but not in the Pacific), and great shearwaters (*Puffinus gravis* in the Atlantic); all Procellariiformes, suggesting this group is particularly vulnerable to plastic ingestion. Indeed, our power analysis demonstrates that much greater sample sizes may be needed for different species and regions within Canada because of species-specific variation and trends.

What species appear to be low risk for plastics ingestion?

A number of species have been examined in large numbers with no evidence of ingested plastics found. Loons and sea ducks generally have no or very little ingested debris (Avery-Gomm et al. 2013; Provencher et al. 2014). Common eiders in particular have been examined for ingested plastics in several locations and time periods with only a single eider ever having been found to have accumulated ingested debris (Provencher et al. 2014). In general, loons and sea ducks appear to be at very low risk of ingesting plastics. This is likely due to the diving foraging strategy employed by these species (i.e., plastics are likely to be encountered at the water surface due to buoyancy, specific gravity, or entanglement in debris along tidal rips and upwellings; Moser and Lee 1992; Avery-Gomm et al. 2013). Low levels of ingested plastics may also be related to the fact that use of these species are restricted principally to coastal marine environments. Although coastlines, including rivers and upstream sources, are likely large sources of plastics as opposed to oceanic dumping at sea, currents and tides appear to concentrate most plastics in more pelagic habitats (Law et al. 2010; UNEP 2011). With this in mind, local current and oceanographic features along with species geographic range need to be considered whenever plastic ingestion data are reviewed.

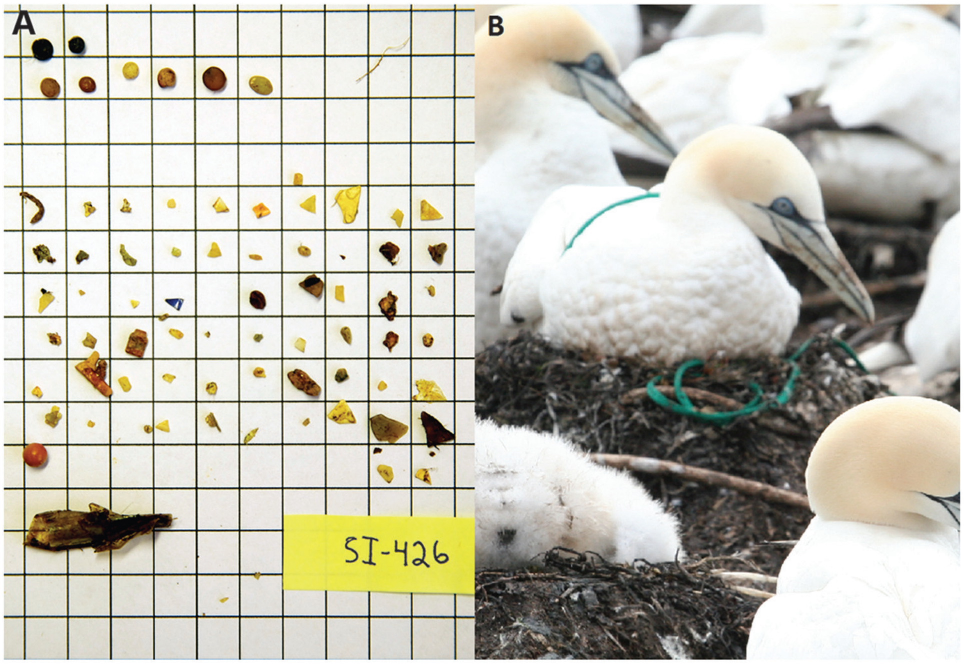
For which species do we have data on the mass of plastic ingested?

Although ingested plastic prevalence is the most reported metric available in the literature, the most biologically important metric of ingested plastic, which is easily obtained and commonly reported, is the mass of plastics in the bird (van Franeker and Meijboom 2002). The mass of ingested plastics is the basis of the North Sea Ecological Quality Objective (EcoQO; van Franeker and Meijboom 2002):

> "There should be less than 2% (<10% by year …) of Northern Fulmars having 0.1 g or more plastic in the stomach in samples of 50–100 beach-washed fulmars from each of 5 different regions of the North Sea over a period of at least 5 years".

Detailed plastics data, including mass of plastics per bird, are available from six species in Canada (7%; northern fulmar, Cory's shearwater (*Calonectris diomedea*), sooty shearwater, great shearwater, common murre, thick-billed murre). Of these six species, only four species have data from all of the regions in which they are found; the northern fulmar in all three regions (Atlantic, Pacific,

Fig. 2. (A) Ingested macro- and microplastics found in a northern fulmar found beached on Sable Island, Nova Scotia (each square measures 1 cm × 1 cm). (B) Plastic incorporation by a northern gannet into a nest on Funk Island, Newfoundland (photo courtesy of W.A. Montevecchi).



Arctic), common murres in both the Pacific and Atlantic, and Cory's shearwater and great shearwater in the Atlantic.

For which species can we assess temporal trends?

To achieve reliable time trends of both prevalence and mass for ingested plastics assessed through necropsies, van Franeker and Meijboom (2002) recommended collection of ≥40 individuals per year over 4–8 years. Annual sampling is obviously ideal to acquire reliable trend data. Increased frequency of sampling over time is also likely to decrease the sample size needed in any given year as the CV metric will decrease as the variance in the samples declines. Unfortunately, annual sampling has not been undertaken in many regions, and instead species are collected over just a short period for assessment.

Using data from birds that have been found in Canada, we assessed what sample sizes would be needed to detect a change of 20% in prevalence with an annual sampling of birds. For thick-billed murres in Newfoundland, 61 birds per year for 4 years would be required (Fig. 3A). Sampling murres for various research projects often approach this number, suggesting that we currently have the statistical power to assess changes in plastic ingestion in this species by coordinating with existing research efforts. To detect changes in common murres from Newfoundland, up to 613 individuals per year would be needed to assess changes, which is considerably higher than most sampling efforts to date (Table 2; Fig. 3B). This suggests that we do not currently have the power to assess changes in this species at the 20% change level.

One hundred and ninety-three northern fulmars must be sampled in the Arctic, whereas only 18 individuals are needed at Sable Island on the Atlantic coast to assess a 20% detectable change in plastic prevalence (Figs. 3C and 3D). As sample sizes at Sable Island usually meet this minimum (Bond et al. 2014), sample sizes from Arctic locations are often well below this value (Provencher et al. 2009). Additionally, as sampling of >20 fulmars per year at Sable Island has occurred over many years, Arctic sampling of northern fulmars has not been done in continuous years. We, therefore, only have sufficient statistical power to detect changes in northern fulmar plastic ingestion on the southern Atlantic Coast of Canada.

For incorporation of plastics into nests by northern gannets, we determined that 187 and 42 nests at Funk Island and Cape Saint Mary's, respectively, would need to be assessed on an annual basis to assess for a 20% detectable change in prevalence (Figs. 3E and 3F). Although samples sizes in a given year often greatly exceed these values at both sites, annual sampling has not occurred regularly at either location. This greatly reduces our ability to accurately and reliably detect changes over time.

Annual sampling is obviously ideal, but where annual samples cannot be acquired, intermittent sampling will require extremely long time series, or very large sample sizes, to detect trends (as discussed for mercury monitoring by Rigét et al. 2011). Ingested plastics in thick-billed murres (Atlantic only) are the only data available from multiple years in the same region, in suitable sample sizes to assess trends. Thick-billed murres sampled in the 1980s, 1990s, and early 2010s off eastern Newfoundland showed no change in ingested plastics prevalence, but the samples indicated a peak of intensity of plastic ingestion in the 1990s (Bond et al. 2013). Other species have been examined over shorter time periods (i.e., sooty shearwaters, great shearwaters, and northern fulmars) at locations in Canada, but analyses of trend data over time has been hampered by inconsistent sampling (Bond et al. 2014).

Knowledge gaps

Despite the work that has been done since the 1960s in assessing how seabirds interact with plastic debris, there are still large data gaps where we know little to nothing about plastic pollution for some species and habitats. For example, we lack any knowledge on plastic ingestion for the majority of Canadian seabirds (57%, Table 1), even when including species where only one individual has ever been examined for plastic ingestion in Canada (e.g., Stejneger's petrel or harlequin duck (*Histrionicus histrionicus*); Table 3).

More specifically, there is a paucity of ingested plastics data for birds from inland water regions of Canada. For many inland areas, the lack of published plastic ingestion or nest incorporation for marine birds is low because of the general lack of research on many of these species (e.g., black terns (*Chlidonias niger*) or Franklin's

Table 2. Species with multiple publications of plastic debris and seabirds in Canadian waters.

Group/Species	Region	Sampling year	Most recent reported incidence (*n*)	Type of debris interaction	Source
Procellariiformes					
Northern fulmar (*Fulmarus glacialis*)					
	Arctic	2002	36 (42)	Ingested	Mallory et al. 2006
	Arctic	2003–2004	31 (102)	Ingested	Mallory 2008
	Arctic	2008*	84 (25)	Ingested	Provencher et al. 2009
	Atlantic	2001–2012	93 (176)	Ingested	Bond et al. 2014
	Pacific	1987	100 (3)	Ingested	Blight and Burger 1997
	Pacific	2009–2010	97 (36)	Ingested	Avery-Gomm et al. 2012
Leach's storm-petrel (*Oceanodroma leucorhoa*)					
	Atlantic	1962–1964*	28 (14)	Ingested	Rothstein 1973
	Atlantic	1987–1988*	5 (749)	Regurgitate	Provencher et al. 2014
	Atlantic	2002–2006*	6 (224)	Regurgitate	Provencher et al. 2014
	Atlantic	2012	48 (63)	Induced regurgitation/ingested	Bond and Lavers 2013
	Pacific	1987	100 (1)	Ingested	Blight and Burger 1997
Sooty shearwater (*Puffinus griseus*)					
	Atlantic	2000–2011	72 (50)	Ingested	Bond et al. 2014
	Pacific	1987	75 (20)	Ingested	Blight and Burger 1997
	Pacific	2011	100 (1)	Ingested	Avery-Gomm et al. 2013
Sulliformes					
Northern gannet (*Morus bassanus*)					
	Atlantic	1989*	97 (741)	Nest incorporation	Montevecchi 1991
	Atlantic	2007*	28 (1080)	Nest incorporation	Bond et al. 2012
Charadriiformes					
Common murre (*Uria aalge*)					
	Atlantic	1996–1997*	2 (60)	Ingested	Bond et al. 2013
	Atlantic	2012*	9 (11)	Ingested	Bond et al. 2013
	Pacific	1987	0 (1)	Ingested	Blight and Burger 1997
	Pacific	2007–2010*	3 (32)	Ingested	Avery-Gomm et al. 2013
Thick-billed murre (*Uria lomvia*)					
	Atlantic	1985–1986*	8 (1249)	Ingested	Bond et al. 2013
	Atlantic	1996–1997*	5 (310)	Ingested	Bond et al. 2013
	Atlantic	2012*	9 (32)	Ingested	Bond et al. 2013
	Arctic	2008*	11 (186)	Ingested	Provencher et al. 2010
Rhinocerous auklet (*Cerorhinca monocerata*)					
	Pacific	1987	0 (6)	Ingested	Blight and Burger 1997
	Pacific	2008–2010	0 (24)	Ingested	Avery-Gomm et al. 2013
Atlantic puffin (*Fratercula arctica*)					
	Atlantic	1999	0 (2)	Ingested	Provencher et al. 2014
	Atlantic	2004	7 (14)	Ingested	Provencher et al. 2014
Anseriformes					
Common eider (*Somateria molissima*)					
	Arctic	1998–2003	0 (388)	Ingested	Provencher et al. 2014
	Arctic	2000–2002	0 (108)	Ingested	Provencher et al. 2014
	Arctic	2011	1 (100)	Ingested	Provencher et al. 2014
King eider (*Somateria spectabilis*)					
	Arctic	2001	0 (3)	Ingested	Provencher et al. 2014
	Arctic	2011	0 (10)	Ingested	Provencher et al. 2014

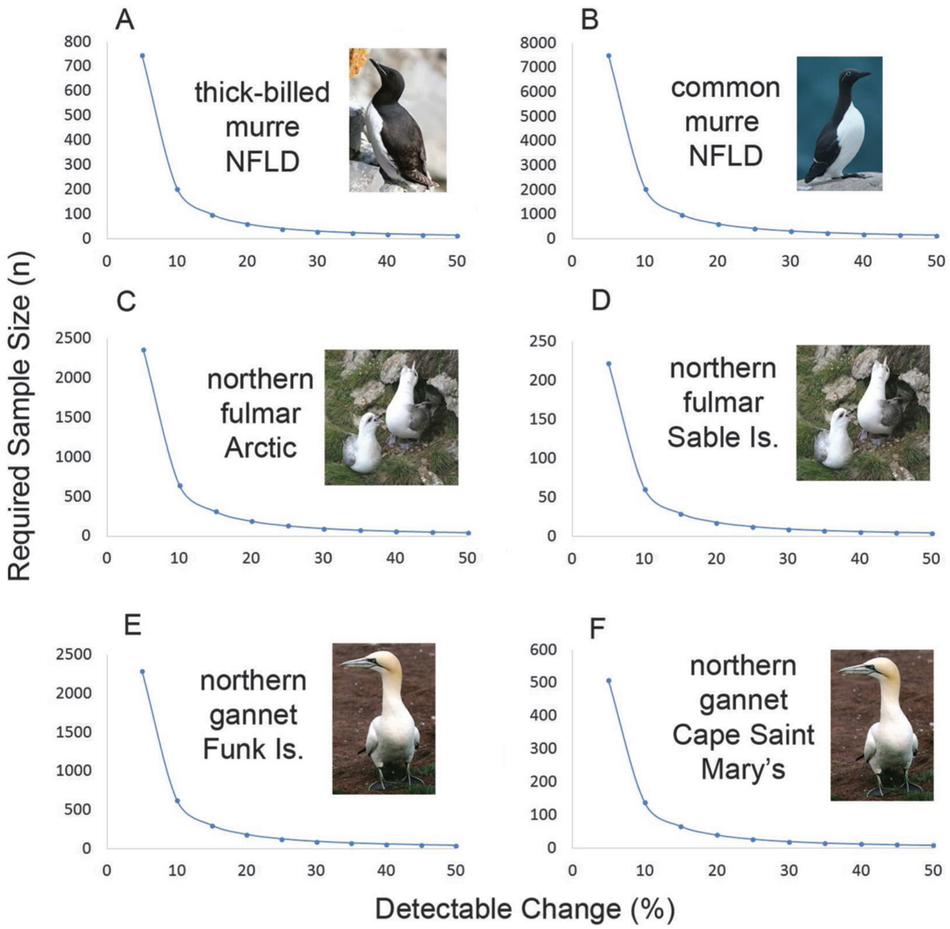
*Indicates plastic interactions (ingestion and nest incorporation) reported for multiple sites.

gulls (*Leucophaeus pipixcan*)). Plastic pollution is likely to be less concentrated in inland waters as compared to oceanic regions where currents and tides cause areas of garbage convergence (Law et al. 2010), but there are regions in Canada where inland waters are subject to large amounts of pollution from shipping and local population centres, specifically the Great Lakes region and the St. Lawrence River (Eriksen et al. 2013). There are large gull and cormorant colonies that are studied intensively in these regions (Hebert et al. 2008), but ingested plastics or plastic nest incorporation data are not readily available. There are ingested plastics data from inland black-billed magpies (*Pica hudsonia*; Reebs and Boag 1987), so it is likely that inland waterbirds are also ingesting plastics with unknown impacts.

Canada lags behind in the understanding of prevalence and trends in plastic pollution in wildlife that is found in other countries, such as those around the North Sea, and there is no large-scale effort to assess plastic ingestion in marine birds in Canadian waters. In the North Sea, where an annual monitoring program has been in place since 1995 (and as far back as the 1980s in some locations), the prevalence, intensity, mass, and composition of ingested plastics are being assessed over time as an indicator of mitigation and cleanup efforts, as well as the state of the ecosystem (van Franeker et al. 2011). Similarly, repeated sampling since the 1980s of South Atlantic seabirds has detected a decrease in industrial plastic pollution over time, attributed to better handling practices in the private sector (Ryan 2008). As a result, although we may know something about plastics in 43% of Canadian seabird species, our knowledge for many species suffers from low samples, inconsistent methodologies, and large temporal gaps (Bond et al. 2013). There are sufficient data for only a few seabird species in some regions in Canada for a robust assessment of changes in plastic ingestion or nest incorporation on an annual basis.

As ingested plastics in some groups have been relatively well-studied in Canadian waters (e.g., the auks (Alcidae)), large data

Fig. 3. Power analysis graphs for (A) thick-billed murres plastic ingestion in Newfoundland, (B) common murre plastic ingestion in Newfoundland, (C) northern fulmar plastic ingestion in the Arctic, (D) northern fulmar plastic ingestion at Sable Island, (E) nest incorporation of plastics by northern gannets at Funk Island, Newfoundland, and (F) nest incorporation of plastics by northern gannets at Cape Saint Mary's.



gaps still exist for other groups such as the gulls (Laridae). Thirteen of the 49 species (27%) in Canada where no data are currently available on ingested plastics are gull species. Although many gull species have not been examined within Canada, ingested plastics have been found in larids inhabiting regions that border Canada (Hays and Cormons 1974; Lindborg et al. 2012), suggesting that Canadian gulls are likely also experiencing ingested plastic pollution. Indeed, the scavenging nature of many gull species should make them particularly susceptible to plastic pollution. Gulls can often regurgitate indigestible material through boluses. This combination of attributes may lend gulls to being useful study species for plastics for specific geographic regions and time periods (e.g., Lindborg et al. 2012).

Future areas of study

Seabirds can be an integral part of plastic litter monitoring and research in Canada. Depledge et al. (2013) and Vegter et al. (2014) recently reviewed and summarized what is known about plastic litter, what can be done to mitigate plastic pollution, the emerging questions regarding plastic litter in the sea, and what actions need to be taken. Seabirds are a key group that can help answer many of the points put forth, including understanding the geographic spread of litter, the damage to marine organisms, and the kinds of organisms that are most affected. Seabirds are also important components to two future recommendations by Depledge et al. (2013): monitoring the trends and effects of plastic litter at sea, and using sentinel species to evaluate the presence and effects of plastic at sea through integrated monitoring strategies. Canada can contribute to many of these emerging questions using seabird studies on all three of its coastlines.

Specifically, future efforts for examining ingested marine debris in marine birds can be divided into two components: (*i*) monitoring for trends; and (*ii*) research on ingested debris including patterns of ingestion across geographic regions, between taxonomic groups, and within age classes of birds. Both monitoring and research in this area are crucial to understanding the distribution of marine debris, and how it may affect seabirds.

To monitor the trends in plastic pollution at sea, efforts should focus on targeted sentinel species (e.g., northern fulmar) that are widely distributed, and known to accumulate marine debris through an integrated national strategy. Focused efforts on targeted species will allow tracking of changes over time and facilitate comparisons with other regions. In addition to monitoring marine debris using seabirds, there are several areas of research where other efforts should be directed.

To improve our understanding of the geographic distribution of plastic pollution in Canada, research should concentrate on species found in two or three of Canada's oceanic domains (Atlantic, Pacific, Arctic) to increase regional comparisons. In Canada, the northern fulmar is found in all three of the coastal regions, where it ingests plastic with relatively high frequency (Provencher et al. 2009; Avery-Gomm et al. 2012; Bond et al. 2014). Future monitoring efforts should leverage the knowledge already in place through established protocols and the existing network of researchers in the North Sea and other regions using this species to monitor

Table 3. Most recent plastic interactions data (ingestion and nest incorporation) from seabirds recovered/collected from regional zones in Canadian waters.

Group/Species	Region	Year of most recent sampling	Most recent reported incidence (*n*)	Type of debris interaction	Source
Procellariiformes					
Diomedeidae					
Black-footed albatross (*Diomedea nigripes*)					
	Pacific	1987	100 (3)	Ingested	Blight and Burger 1997
Procellariidae					
Northern fulmar (*Fulmarus glacialis*)					
	Arctic	2008	84 (25)	Ingested	Provencher et al. 2009
	Atlantic	2001–2012	93 (176)	Ingested	Bond et al. 2014
	Pacific	2009–2010	97 (36)	Ingested	Avery-Gomm et al. 2012
Stejneger's petrel (*Pterodroma Iongirostris*)					
	Pacific	1987	100 (1)	Ingested	Blight and Burger 1997
Sooty shearwater (*Puffinus griseus*)					
	Atlantic	2000–2011	72 (50)	Ingested	Bond et al. 2014
	Pacific	2011	100 (1)	Ingested	Avery-Gomm et al. 2013
Great shearwater (*Puffinus gravis*)					
	Atlantic	2000–2011	88 (84)	Ingested	Bond et al. 2014
Cory's shearwater (*Calonectris diomedea*)					
	Atlantic	2003–2005	0 (3)	Ingested	Bond et al. 2014
Hydrobatidae					
Leach's storm-petrel (*Oceanodroma leucorhoa*)					
	Atlantic	2002–2006	6 (224)	Regurgitate	Provencher et al. 2014
	Pacific	1987	100 (1)	Ingested	Blight and Burger 1997
Fork-tailed storm-petrel (*Oceanodroma furcata*)					
	Pacific	1987	100 (7)	Ingested	Blight and Burger 1997
Pelecaniformes					
Phalacrocoracidae					
Double-crested cormorant (*Phalacrocorax auritus*)					
	Pacific	2009–2010	0 (2)	Ingested	Avery-Gomm et al. 2013
Northern gannet (*Morus bassanus*)					
	Atlantic	2007	28 (1080)	Nest incorporation	Bond et al. 2012
Charadriiformes					
Laridae					
Great black-backed gull (*Larus marinus*)					
	Atlantic	1966–1967	<17 (32)	Ingested	Threlfall 1968
	Atlantic	1969–1970	1 (816)	Bolus	Lock 1973
	Atlantic	1988–1989	Relatively high (199 nests)	Chick regurgitation	Gilliland et al. 2004
	Atlantic	2011	<10 (20)	Nest incorporation	R. Ronconi unpublished data
Glaucous-winged gull (*Larus glaucescens*)					
	Pacific	2010	33 (3)	Ingested	Avery-Gomm et al. 2013
Herring gull (*Larus smithsoniansus*)					
	Atlantic	1966–1967	<14 (401)	Ingested	Threlfall 1968
	Atlantic	1970	2 (690)	Bolus	Lock 1973
Bonaparte's gull (*Chroicocephalus philadelphia*)					
	Atlantic	1978–1979	8 (25)	Ingested	Braune and Gaskin 1982
Ivory gull (*Pagophila eburnea*)					
	Arctic	2002–2010	1 (97)	Nest incorporation	M. Mallory unpublished data
Black-legged kittiwake (*Rissa tridactyla*)					
	Atlantic	1966–1967	<26 (69)	Ingested	Threlfall 1968
Arctic tern (*Sterna paradisaea*)					
	Atlantic	1978–1979	0 (19)	Ingested	Braune and Gaskin 1982
	Arctic	2007	0 (41)	Ingested	Provencher et al. 2014
Common tern (*Sterna hirundo*)					
	Atlantic	1978–1979	17 (6)	Ingested	Braune and Gaskin 1982
Alcidae					
Common murre (*Uria aalge*)					
	Atlantic	2012	9 (11)	Ingested	Bond et al. 2013
	Pacific	2007–2010	3 (32)	Ingested	Avery-Gomm et al. 2013
Thick-billed murre (*Uria lomvia*)					
	Atlantic	2012	9 (32)	Ingested	Bond et al. 2013
	Arctic	2008	11 (186)	Ingested	Provencher et al. 2010
Razorbill (*Alca torda*)					
	Atlantic	2011–2012	0 (8)	Ingested	Provencher et al. 2014
Dovekie (*Alle alle*)					
	Atlantic	2012	14 (65)	Ingested	D. Fife unpublished data

Table 3 (*concluded*).

Group/Species	Region	Year of most recent sampling	Most recent reported incidence (*n*)	Type of debris interaction	Source
Rhinoceros auklet (*Cerorhinca monocerata*)					
	Pacific	2008–2010	0 (24)	Ingested	Avery-Gomm et al. 2013
Cassin's auklet (*Ptychoramphus aleuticus*)					
	Pacific	2010	0 (1)	Ingested	Avery-Gomm et al. 2013
Pigeon guillemot (*Cepphus columba*)					
	Pacific	2006–2010	0 (9)	Ingested	Avery-Gomm et al. 2013
Marbled murrelet (*Brachyramphus marmoratus*)					
	Pacific	2005–2010	0 (7)	Ingested	Avery-Gomm et al. 2013
Ancient murrelet (*Synthliboramphus antiquus*)					
	Pacific	2009	0 (5)	Ingested	Avery-Gomm et al. 2013
Scripps's murrelet (*Synthliboramphus scrippsi*)					
	Pacific	1987	0 (5)	Ingested	Blight and Burger 1997
Atlantic puffin (*Fratercula arctica*)					
	Atlantic	2004	7 (14)	Ingested	Provencher et al. 2014
Horned puffin (*Fratercula corniculata*)					
	Pacific	1987	50 (2)	Ingested	Blight and Burger 1997
Tufted puffin (*Fratercula cirrhata*)					
	Pacific	1987	89 (9)	Ingested	Blight and Burger 1997
Gaviiformes					
Gaviidae					
Red-throated loon (*Gavia stellata*)					
	Pacific	2010	0 (2)	Ingested	Avery-Gomm et al. 2013
Common loon (*Gavia immer*)					
	Pacific	2010	0 (2)	Ingested	Avery-Gomm et al. 2013
Pacific loon (*Gavia pacifica*)					
	Pacific	2010	0 (2)	Ingested	Avery-Gomm et al. 2013
Anseriformes (Merginae only)					
Anatidae					
King eider (*Somateria spectabilis*)					
	Arctic	2011	0 (10)	Ingested	Provencher et al. 2014
Common eider (*Somateria mollissima*)					
	Arctic	2011	1 (100)	Ingested	Provencher et al. 2014
Surf scoter (*Melanitta perspicillata*)					
	Atlantic	2006	0 (38)	Ingested	Provencher et al. 2014
	Pacific	2010	0 (2)	Ingested	Avery-Gomm et al. 2013
Harlequin duck (*Histrionicus histrionicus*)					
	Pacific	2010	0 (1)	Ingested	Avery-Gomm et al. 2013
Long-tailed duck (*Clangula hyemalis*)					
	Arctic	1998–1999	0 (27)	Ingested	Provencher et al. 2014

Note: < indicates values where marine plastic and garbage was included in a category that also included natural debris such as rocks.

changes and trends in marine pollution (Provencher et al. 2009; van Franeker et al. 2011; Avery-Gomm et al. 2012; Kühn and van Franeker 2012; Donnelly-Greenan et al. 2014). In addition, expanding efforts in monitoring debris ingestion to other pan-Canadian species such as Leach's storm-petrels (*Oceanodroma leuchorhoa*) and common murres (found on both the Atlantic and Pacific coasts) would augment our knowledge of debris in the oceanic environment. In particular, we recommend the addition of other monitoring species that have different foraging strategies (e.g., common murres: deep-water pursuit diving; Leach's storm-petrel: surface seizing), as this will improve our sampling of different components of the marine environment, and thus our understanding of plastic pollution in the ecosystem.

There are no northern fulmars or Leach's storm-petrels in Canada's inland regions, including the Great Lakes and the Gulf of St. Lawrence. To assess plastic pollution in this region, different species, and perhaps protocols, need to be identified and developed. This is an area where expanded efforts in species that are widely distributed and already intensively studied (e.g., double-crested cormorants (*Phalacrocorax auritus*) and herring gulls (*Larus argentatus*)) may be warranted (Hebert et al. 2008). Although the physical properties of inland water bodies are different from oceans, a monitoring program to track marine debris would augment other lake clean-up and conservation (de Pinto et al. 1986; Hartig and Thomas 1988).

Several species have very high levels of plastic ingestion, but due to small sample sizes available from Canadian waters, it is difficult to make accurate ingestion assessments or use these species for regular monitoring. For example, in some nonbreeding species, such as the Laysan albatross (*Phoebastria immutabilis*), monitoring plastic ingestion is done much more effectively at breeding colonies outside Canada where sampling can be done at a large scale (e.g., Young et al. 2009). Other species are also found in other regions more often (e.g., black-footed albatross), resulting in larger sample sizes and more accurate assessments (Gray et al. 2012) in those regions as compared with individuals from Canadian waters. Such species should be assessed when available and preferably in collaboration with researchers working on the breeding grounds, but they should not be considered for large-scale monitoring or research efforts within the Canadian context.

To better understand the sources of plastics entering seabirds and other higher trophic level predators, future studies should also focus on the routes of seabird ingestion (i.e., direct from the environment or via prey species). Studies have shown that some species of fish may be more susceptible to ingesting plastics, and thus may contain a larger plastic load when then consumed by seabirds (Boerger et al. 2010). Assessing vectors of contamination in seabirds from prey items versus direct consumption needs to be better understood as this may influence possible mitigation efforts in a dynamic management framework.

In addition, to gain a better understanding of seabird interactions with marine plastics, both macro- and microplastics, seabird ingestion studies should be tied to regions where plastic pollution is also being assessed within the water column. Regional studies have shown that both macro- and microplastics are common in regions of seabird habitat (Williams et al. 2011; Desforges et al. 2014). Matching seabird studies with such environmental studies will increase our knowledge of the patchiness of plastic pollution, and how this may affect seabird ingestion and nest incorporation.

Although we focus on monitoring plastics in the marine environment for this particular review, we recognize and encourage studies that also examine the impacts of plastics on seabirds, and critically examine appropriate effect threshold levels for sentinel species. Furthermore, understanding the causes and rates of indirect effects of plastic ingestion, such as contaminant transfer or physical damage to the gastrointestinal tract, should focus on species that are available in large numbers and have a high prevalence and intensity of ingested marine plastics.

A national strategy for monitoring plastic pollution

In addition to increasing our understanding of which species ingest plastics, and in what quantities (including filling species and geographical knowledge gaps), we propose a national strategy for monitoring plastic pollution in Canadian waters using aquatic birds. This strategy is based on our existing knowledge, and uses multiple indicators. While annual monitoring would be ideal, it is logistically challenging in many areas, notably in the Canadian Arctic. We urge monitoring at no more than 3-year intervals of the following:

1. Plastic ingestion by northern fulmars in the Atlantic, Pacific, and Arctic, following the methods established in the North Sea (van Franeker et al. 2011), i.e., a minimum of 40 birds in each region during each sampling year with greater sample sizes (as many as 80) in the Arctic if possible. Northern fulmars ingest plastic in high frequencies, are distributed throughout Canadian waters, and can be compared with studies in Europe and other parts of the Atlantic and Pacific (Provencher et al. 2009; Avery-Gomm et al. 2012; Bond et al. 2014; Donnelly-Greenan et al. 2014). Such studies would address differences in plastic pollution between regions, and also allow examination of trends in plastic pollution over time. In addition, these study results would then be useful to carry out power analysis for other metrics such as mass and type of plastic beyond prevalence.
2. Plastic ingestion by common and thick-billed murres in Newfoundland (both species), thick-billed murres in the Arctic, and common murres in British Columbia. A sample of gastrointestinal tracts can be obtained from harvesters during the annual murre hunt in Newfoundland (Bond et al. 2013), from hunters in Nunavut (Provencher et al. 2010), and from beached common murres in British Columbia (Hamel et al. 2009). Although the sources of the samples will differ, van Franeker and Meijboom (2006) showed northern fulmars that died from different methods (beached birds versus those that died from ship strikes) showed no difference in plastic ingestion metrics. While 60 thick-billed murres should be collected, if possible 200 common murres should be obtained to accurately assess prevalence and changes over time. Murres ingest plastic at relatively low frequencies (Provencher et al. 2010; Bond et al. 2013), but there are data from the 1980s, 1990s, and early 2010s from harvested birds in Newfoundland making this set of species one of the best studied to date (Bond et al. 2013). Continued analysis of thick-billed and common murres would also address spatial and temporal trends in plastic pollution. These collections also provide insight into how foraging ecology may influence risk, thereby guiding conservation efforts. Murres also provide an indication of ocean condition in inshore waters, as compared with northern fulmars and other more pelagic species.
3. Plastic ingestion by Leach's storm-petrels in Atlantic Canada and British Columbia. Storm-petrels range past the continental shelf (Pollet et al. 2014), and they accumulate plastic in low amounts but with relatively high frequency (Bond and Lavers 2013). Procellariiformes offload plastic to their chicks, so sampling during incubation is required to assess adult plastic burdens. Samples from regurgitations during incubation can be used to track potential changes in frequency and amount of plastics ingested by these birds (Provencher et al. 2014). In the long term, a power analysis is needed to determine appropriate samples sizes, but a reasonable goal is a minimum of 100 individuals per site per year.
4. Incorporation of debris in northern gannet nests at Cape St. Mary's and Funk Island, Newfoundland and Labrador, and Bonaventure Island, Quebec, each year the colonies are visited. A minimum of 629 nests should be assessed at Funk Island and 140 at Cape Saint Mary's each year to be able to determine a 10% change. These colonies are relatively easily accessible, and the rates of plastic incorporation vary between the colonies, with higher rates at Cape St. Mary's (Bond et al. 2012). These studies are useful in indicating changing types of plastic pollution, and they can continue to track trends through the established monitoring program at little additional cost.
5. Incorporation of debris into nests of double-crested cormorants. Similar to nest incorporation by northern gannets, assessing plastic pollution in cormorant nests offers a relatively easy and noninvasive way to monitor plastic pollution in inland areas. Again, many colonies are already visited by research programs, and this assessment could be integrated into the larger objectives. Although no data are currently available from Canadian waters, we recommend an assessment of 100 nests in each region per year as an initial trial. A power analysis and reassessment of the findings could then shape how future efforts should continue.
6. Bolus collection from inland gull species (e.g., Lindborg et al. 2012). There are several programs that study inland gulls (e.g., on the Great Lakes; Hebert et al. 2008). Bolus collection is low impact, can be done for colonies where current study programs exist with little extra cost, and can be done at a variety of locations that represent degrees of exposure to urban areas. Bolus collection can also be done for a variety of species, can be compared across geographic regions giving potential insights into differences between inland areas, and can include members of the public through citizen science campaigns (Lindborg et al. 2012).

Conclusions

Plastic pollution is ubiquitous in the marine environment and is a growing concern for many species. This review indicates that marine birds on all three of Canada's coastlines are susceptible to plastic pollution. Even species in the remotest of environments, like the endangered ivory gull (*Pagophila eburnea*) in the high Arctic, have the potential to be influenced by plastic pollution. Baseline data and a regular monitoring program may be particularly important in Canada as many northern birds may be particularly susceptible to marine plastic pollution as global climate changes release large amounts of plastics currently trapped in ice (Obbard et al. 2014).

As the widespread and far-reaching implications of marine plastic pollution are increasingly recognized, the call for better assessment of plastic pollution to help support monitoring and regulation is growing (Depledge et al. 2013; UNEP 2014; Vegter et al. 2014). Seabirds offer historic data on plastic pollution to better detect change, and they are a relatively widespread and economical way to study marine plastics over a large and disperse geographic area. With Canada's extensive coastline and three oceans, using sentinel species such as seabirds is one of the best options for Canada to assess plastic pollution in all three of Canada's oceans.

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